Carbon, Sulfur and Mercury—A Biogeochemical Axis of Evil

George Aiken
United States Geological Survey

I welcome this opportunity to come and preach the gospel according to Aiken, which is that to really understand ecosystems we need to pay much more attention to reactions involving natural organic matter. It's taken me many years to convince my colleagues of the important role of dissolved organic matter (DOM) in the methylation of mercury. Methylmercury is a nasty player—it's a very efficient bioaccumulator that rockets up through the food chain, so even the very low concentrations (nanograms per liter) found in many ecosystems are significant. In most aquatic environments mercury is atmospherically deposited. Here in the Delta, we also have mercury from naturally occurring deposits, as well as from historic mercury and gold mining, coming in from the upstream watershed. Methylmercury is produced at the sediment-water interface by sulfate-reducing bacteria.

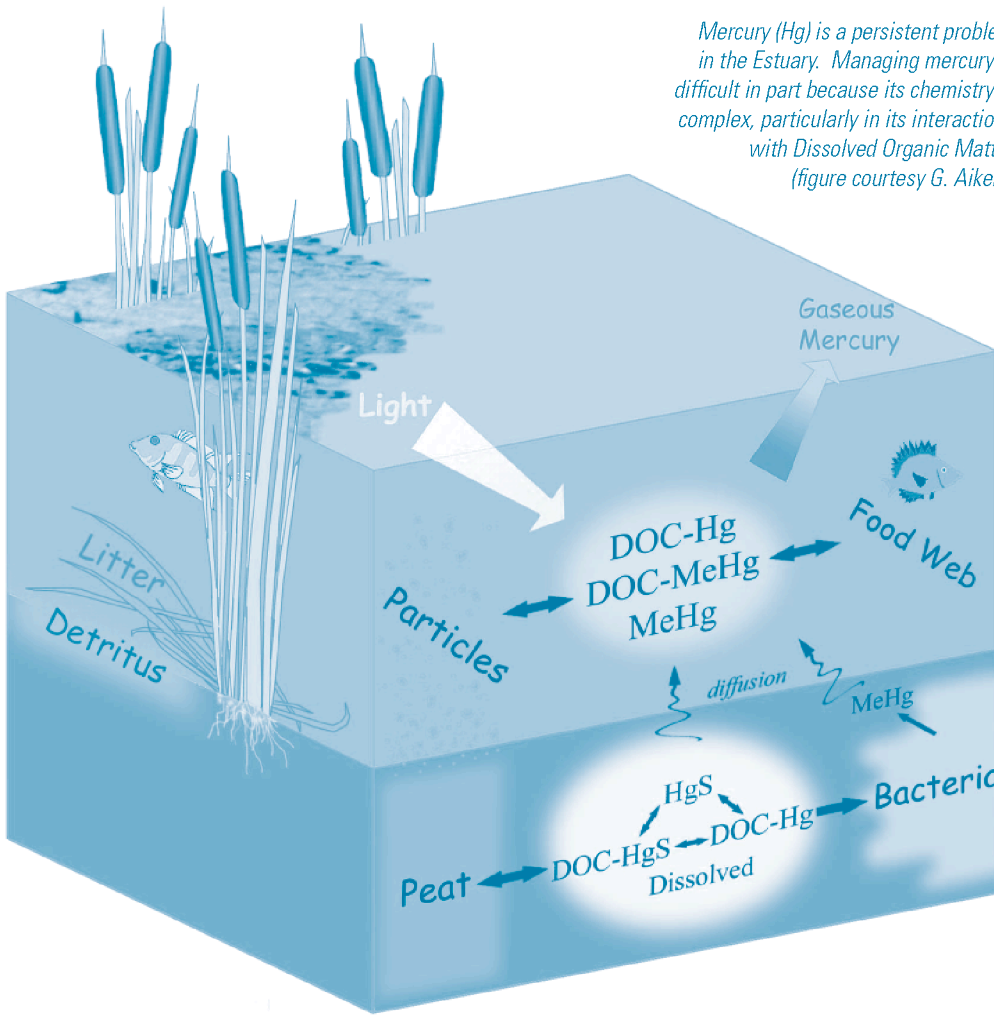
> "Methylmercury is a nasty player—it's a very efficient bioaccumulator that rockets up through the food chain..."

Over the last seven years studying mercury cycling in the Florida Everglades, we've learned many lessons that are important here in California. Our work is particularly concerned with HgS-DOM interactions and how they affect the availability of mercury to the sulfate-reducing bacteria. There are several difficulties in studying these interactions. One is that we have a thousand and one molecules in our DOM and only a small percentage of them interact strongly with mercury, so we can't write an equation and define the interaction with kinetic and thermodynamic expressions. Another is that the chemical equilibrium approach really doesn't explain mercury behavior in the systems that we're studying. And the third is that just measuring mercury and studying its geochemistry at the very low concentrations that are environmentally relevant is very difficult.

Because the DOM is such a complicated mixture of reactive and nonreactive compounds, the quality of the DOM—its composition—is more important than the quantity. For any given ecosystem, we need to be able to characterize the DOM and determine if we have Sleepytime, or do we have Red Zinger for the processes of interest. So our approach is to move beyond just measuring DOM. Using a chromatographic method, we fractionate DOM into five fractions based on polarity and solubility. The hydrophobic organic acids fraction is where most of the aquatic humic materials show up, and it turns out that it's a very reactive fraction for a number of processes, including mercury reactivity. We process many different water samples and freeze-dry the hydrophobic organic acids fraction, which enables us to perform laboratory experiments using real natural organic matter, not a model compound that we hypothesize is going to behave like natural DOM.

In experiments with DOM-Hg binding we have found that at very low concentrations of mercury (roughly 0.001 to 1 micrograms Hg per mg DOM), the binding constant is very large, on the order of 1023, similar to that for organic thiols. This indicates that the sulfur groups in organic molecules are very effective at binding mercury. At higher Hg/DOM ratios (in the range of 10-500 micrograms Hg per mg DOM), the binding constant is about 1011, which reflects binding to carboxyl groups in the DOM. These lower binding constants appear frequently in the literature and in historical data, but they're useless for modeling ecosystems. However, it is only recently that researchers, ourselves included, have been able to measure the binding constants at mercury concentrations that are reflective of real ecosystems. Even though the concentration of the strong binding sites in the DOM is low, it is still significantly greater than the concentration of mercury, so it's the strong binding that drives the system.

Sulfide binds mercury much more strongly than does DOM, so we don't think that the DOM is outcompeting sulfide. We are very interested, therefore, in the behavior of the DOM in the presence of sulfide and HgS. We have investigated two questions. The first is: Can DOM inhibit the precipitation of HgS? The answer is yes. What happens is that the DOM adsorbs to HgS, shutting down the precipitation process and in essence keeping more of the mercury in solution than we would expect. So DOM helps keep the levels of dissolved mercury higher than they would be if HgS was the only driving force. The second question is: Can DOM bring about the dissolution of cinnabar, the mineral form of HgS? The answer to this question is also yes. This is a very important question here in California since a lot of the mercury coming down the Sacramento River into the Delta region is in the form of cinnabar. Our studies showed that the dissolution of cinnabar is not related to the amount of strong binding sites in the DOM, but rather to the amount of aromatic carbon, which we measured by specific UV absorbance. This means that if we know the aromatic carbon content of a sample of DOM, we can predict how reactive that sample will be in solubilizing HgS. Although we didn't use any Delta samples in our experiments, based on existing data on their specific UV absorbance we would expect them to be quite reactive.



Mercury (Hg) is a persistent problem in the Estuary. Managing mercury is difficult in part because its chemistry is complex, particularly in its interactions with Dissolved Organic Matter (figure courtesy G. Aiken).

The big overarching question is what controls the bioavailability of mercury to the bacteria that methylate it. Do the interactions of mercury and DOM enhance or inhibit mercury methylation; do they help or hinder us in the real world? These questions are hard to answer because the pathways for mercury methylation by sulfate-reducing bacteria are still unknown. As one approach to investigating what really happens out in the wetlands, we installed mesocosms in the Everglades and performed experiments by amending the mesocosms with sulfate, low levels of isotopically enriched mercury (allowing us to follow the fate of both the "new" and the ambient mercury), and some of our freeze-dried DOM that we know is Red Zinger in terms of interacting with mercury. We found that when we added DOC more methylmercury was produced, both from the mercury spike and the ambient mercury in the system. Although the specific mechanisms by which this occurs are not yet fully understood, we hypothesize that adding DOM increases the amount of dissolved mercury in the system, and we also know that, in general, dissolved constituents are more bioavailable.

Now let's bring this back to the Delta. What do we have in the Sacramento River? We have mercury, including HgS, and we also have a fairly low level of DOM. And what do we have in the Delta? We have a large amount of DOM, and it's a reactive type of DOM. And there is also sulfate in the system. So when the mercury coming down the river merges with the DOM in the Delta, we get our biogeochemical axis of evil. The practical relevance is that management decisions can influence the amounts of both DOM and sulfate. If we want to be able to make good management decisions we need to understand the processes that control mercury methylation, such as Hg-DOM interactions, so that, for example, we can predict whether establishing more wetland habitat will exacerbate the methylation of mercury.

What Restoration Ecologists Should Know About Mercury

Mark Marvin-DiPasquale (USGS), Jay Davis (SFEI) and Josh Collins (SFEI), Session Chairs

Background

Approximately 10 million pounds of mercury were released to Sierra Nevada streams during gold processing in the mid to late 1800s. Mercury contamination continues from the waste of over 200 known historic gold mines, deposition from air pollution, and mobilization and re-suspension of contaminated sediment. However, the absolute amount of total mercury is not in and of itself the primary concern. Sulfate-reducing bacteria transform inorganic divalent Hg(II) to methylmercury, which is then available for uptake by organisms and bioaccumulation up the food chain. Methylating bacteria are found largely in anoxic sediments and are particularly active in wetlands rich in organics. This puts CALFED wetland habitat restoration goals in potential conflict with water quality goals.

The mercury problem has both a human health dimension and a wildlife dimension. In humans, exposure through consumption of contaminated sport fish can lead to nervous system and organ damage, and is of particular concern for pregnant women, developing fetuses, and children. Methylmercury is also highly toxic to early life stages of fish and birds, with effects varying from subtle neurological disorders impairing reproductive and foraging abilities and eggs that fail to hatch. In addition, recent work indicates that methylmercury may have serious effects due to endocrine disruption, an important new finding that deserves research attention.

Ultimately, elucidating the location and transport of mercury from watersheds through the Delta is only a first step. Developing an understanding of the processes that influence methylmercury formation will be critical to determining whether we can fulfill CALFED's commitments to reducing the impacts of mercury to human health and ecosystem function. Biogeochemistry, geomorphology, and ecology must all be considered if we are to meet our management goals.

As in all scientific endeavors, asking the right questions is the first challenge. Future work will need to be framed properly if research results are to be most useful for effective management of mercury (Collins):

- Are people or special-status wildlife being harmed? Is the harm measurable at the population or community level?
- Should dredged sediments and tailings be utilized in restoration projects?
- What are the harmful sources and pathways? Can we rank specific sources of mercury within rivers and marshes (e.g. channels, floodplains, ponds)? In light of tremendous spatial variability in mercury sources, what aspects of the system should we manage to solve the problem?
- How does the mercury problem stack up against biological invasions, impacts on drinking water in the Delta, and the positive aspects of restoration?
- Can science tell us something with enough certainty to justify changing our actions?
- How should we define success? What should we monitor? What happens if we do nothing?

MANAGEMENT IMPLICATIONS

- Reducing the production of methylmercury in aquatic ecosystems could help reduce its accumulation in the aquatic food chain. A Mercury Strategy developed by CBDA to address this issue has seven components: (1) assessment of mercury sources, (2) remediation of mercury sources, (3) assessment of restoration actions on methylmercury exposure, (4) monitoring of mercury in sport fish and bioindicator organisms, (5) assessment and communication of human-health risk, (6) assessment of ecological risk, and (7) identification of potential management approaches for reducing methylmercury contamination (Wiener).
- Reducing methylmercury exposure in humans could be accomplished through: (1) reduction of mercury releases, (2) provision of fish-consumption advice, and (3) management of contaminated landscapes to decrease production and bioaccumulation of methylmercury (Wiener).
- Small fish and invertebrate ("biosentinel") methylmercury levels correlate well with sport fish levels and are an excellent monitoring tool. Biosentinel monitoring could be used as a biologically relevant and statistically defensible performance measure for restoration and remediation projects (Slotton).
- The "do nothing" approach to mercury contamination over

SCIENTIFIC INFORMATION

- Wetlands have huge diversity in organic matter quality, salinity, redox conditions, mineralogy, and food web structure, all of which influence mercury cycling. Net methylmercury production is a function of microbial activity and available mercury: and only a small fraction of total mercury in the system is available for methylation. The degree of methylmercury production varies greatly on spatial scales from centimeters to regions (Marvin-DiPasquale).
- Methylmercury production varies widely, but predictably, among and within wetlands. In Stevens Creek Marsh, more methylmercury was produced in mudflats during winter compared to pickleweed and bulrush dominated sites. The marsh shifted to higher methylmercury production rates and concentrations in sediments associated with pickleweed during summer. These results suggest both seasonal and spatial shifts in the factors controlling methylmercury production and variation related to vegetation type (Marvin-DiPasquale).
- Large scale studies in Northern California and Louisiana generally suggest the following relative methylmercury production potential rates: salt marsh>> freshwater wetlands>lakes and reservoirs >rivers (Marvin-DiPasquale).
- Use of dredged materials is planned at Hamilton Air Force Base (HAAF) wetlands restoration site. Over the course of sediment sampling studies there, total mercury in soils and sediments remained the same, but methylmercury increased by a factor of three during the wet season. The highest mercury was found in the intertidal zone, and the highest methylmercury occurred closer to the upper levee where it was less influenced by tidal fluctuation. All HAAF sediments were net methylmercury producers. Rainwater or surface water plays a role in mercury methylation in the higher marsh areas (Fredrickson).
- Results of an 18-month methylmercury mass balance indicate methylmercury is not acting conservatively in the Delta. Flooding the Yolo Bypass may cause increased methylmercury in the Delta. The Sacramento River was the major source of methylmercury and accounted for 60-85% percent of total river load (10 g/day). Average flux out of the sediment was about 6 g/day. Input from all 13 sewage treatment plants discharging directly to the Delta was about 0.7 g/day. Urban runoff contributed about 0.1 g/day. Inputs exceeded exports by 10 g/day (Foe).
- Concentrations of methylmercury follow a gradient in the Delta, from high levels near river inputs to lower levels leaving the Delta. 50-100%

-continued

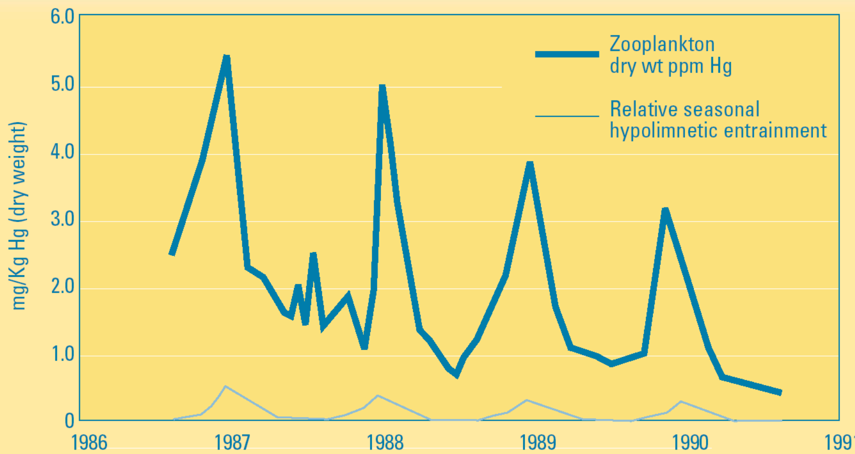
the last 30 years has resulted in consistently high mercury levels in sport fish. Mercury concentrations in striped bass, which are integrative indicators of mercury in the watershed, have not changed perceptibly in the past 30 years. Coastal, Sierra Nevada, and upper Delta sport fish often have high mercury concentrations in their tissue. However, fish mercury contamination in the central and lower Delta is of lower public health concern (Davis).

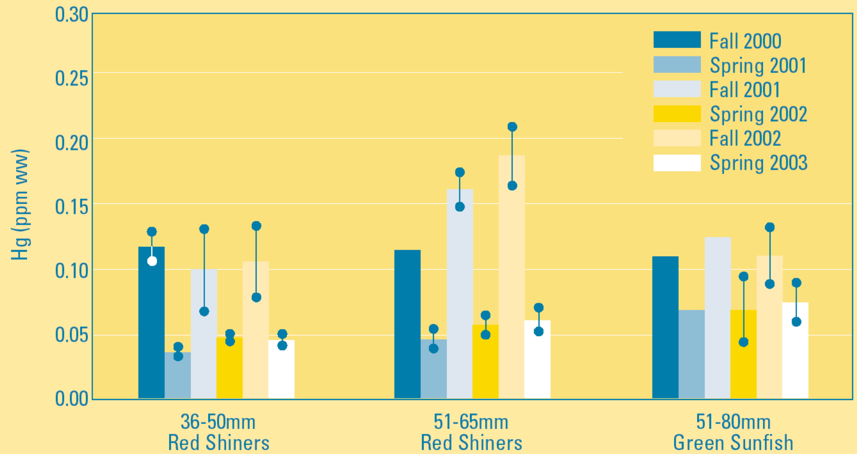
- Potential impacts from disturbance of mercury contaminated sediments trapped behind Daguerre Point Dam in the lower Yuba River are of concern to managers considering dam modification or removal. Mercury released from sediments behind Daguerre Point Dam could methylate in downstream environments and add to the problem of mercury contamination in Bay-Delta ecosystems (Hunerlach).
- Management of mercury in river restoration projects needs to address not only mercury sources and mobility, but other processes that may enhance methylmercury production. Mercury can concentrate in different sizes of sediment, and ponds made from tailings can foster production of methylmercury. Acids and salts increase release of mercury from sediments. Methylmercury production is enhanced in wetland and mine tailing pond environments where sulfate and DOC concentrations are elevated by effluent (Rytuba).
- Dredge tailings may be easier to manage than hydraulic mine tailings because of their more uniform size and lower levels of mercury (Rytuba, Hunerlach).
- Processing tailings slated for use in Merced River habitat restoration could reduce the risk of mercury mobilization. Low mercury levels in tailings may allow re-use in floodplain reconstruction projects away from the channel, and removal of mercury in fine sediment by sorting could reduce the risk of mercury mobilization. Dry sorting of dredger tailings could potentially result in a 50% reduction of near-term mercury release and an even greater reduction in long-term release (Fleming-Singer).

SCIENTIFIC INFORMATION CONTINUED

of methylmercury disappeared near the Rio Vista sampling site, but mechanisms for this loss are unknown (Foe).

- Lower trophic level organisms, small fish and invertebrates ("bio-sentinels") provide a more sensitive measure of variability of methylmercury in aquatic ecosystems than large sport fish (Slotton).
- Fall turnover of anoxic bottom water in reservoirs is a large source of methylmercury (Slotton).
- Largemouth bass, striped bass, Sacramento pikeminnow, channel catfish, and white catfish commonly exceed the 0.3 ppm mercury threshold for human health concern. Mercury concentrations in largemouth bass from the Feather River, northern Delta, lower Cosumnes River, San Joaquin River, and Sierra foothill reservoirs were elevated, while those in the central Delta were lower (Davis).
- There was more mercury in hydraulic mine tailings than in dredge mine tailings at Daguerre Point Dam. Mercury concentrations were higher in the finer size fractions. Overall methylmercury potential production rates of the sediments sampled were low, but mercury in sediments released downstream could be a significant source of mercury to environments where methylmercury production is high (Hunerlach).
- In Clear Creek and Trinity River restoration projects, mercury and methylmercury are concentrated in the fine-grain size fraction of tailings and sediments. Mercury concentrations and resulting methylmercury production can be very high in ponds and wetlands created in mine tailings (Rytuba).
- On the Merced River, measurements indicated low total mercury in dredger fines and higher mercury in fines from in-channel and backwater sites (Fleming-Singer).
- Potential to reduce the risk of mercury mobilization from dredger tailings processing was assessed by selectively removing mercury-laden fines through dry sorting and washing. Processing of tailings by dry sorting leached more mercury than wet sorting, and processing of fines leached more mercury than bigger fractions (Fleming-Singer).





"Biosentinels" can better reveal fine-scale temporal variability in mercury levels than large sport fish. Seasonal (top) and semi-annual (bottom) fluctuations in mercury in Davis Creek Reservoir and Lower Cache Creek are shown here (Figure D. Slotton).

Drinking Water Quality: Protection and Watersheds

William Glaze (OHSU) and
Brian Bergamaschi (USGS)
Session Chairs

Background

Improving water quality is one of the four major goals of the CALFED Bay-Delta Program. Related to drinking water, CALFED's goals include cost effective continuous improvement of source water quality, water management, and treatment. The CALFED ROD includes specific targets for bromide and total organic carbon, or an "Equivalent Level of Public Health protection" (ELPH). These targets are based on reducing harmful disinfection by-products (such as trihalomethanes and bromate) through source improvement. Other constituents of concern for drinking water are pathogens, turbidity, salinity, nutrients, taste and odor causing compounds, and any other compounds that present a threat to public health, including emerging contaminants such as perchlorate, pharmaceuticals, and possibly some personal care products.

CALFED's strategy to improve drinking water quality through ELPH revolves around intervening at multiple points to achieve desired objectives. ELPH recognizes that water quality at the tap is the result of many more factors than treatment alone, and that the most cost-effective solution is a combination of these factors. ELPH includes source improvement, better water management in the Delta, regional and local source water exchanges, and improvements to the conveyance and storage of drinking water. Source water quality protection tools include source watershed management, modification of operations to improve water quality, total maximum daily loads (TMDLs), point and non-point source controls. Ultimately, all ELPH elements funnel through treatment and distribution systems, which are the last line of defense for public health protection. This framework forms the context for the science presented in these sessions.

The challenges facing drinking water quality stem from four major factors: increasingly stringent tap water regulations, high consumer expectations, source water quality degradation due to increased population, and emerging contaminants of concern identified by new science. For example, we can expect decreased freshwater flows and increased urban runoff pollution as populations grow throughout the state, increasing levels of all constituents of concern. Regulations are often linked to source water quality by using the level of a particular constituent to determine the treatment required. Thus, multiple regulations can greatly complicate treatment. Although treatment plants using Delta water currently meet all regulations, plant managers anticipate stricter future regulations, and have taken the initiative to collaborate on research and to explore creative new ways (such as decentralized treatment) to ensure the quality of California's drinking water.

One of the most important water quality constituents of concern is dissolved organic carbon (DOC), which was the focus of much of the science presented in these sessions. DOC affects the efficacy and cost of treatment through the formation of disinfection byproducts (DBPs) such as trihalomethanes (THM), and it can cause problems in distribution systems. The impact of DOC on drinking water quality entwines the issue with land use changes and ecosystem restoration in the Delta and Central Valley. For example, tidal wetlands provide benefits including habitat, improved ecosystem, flood protection and subsidence mitigation, but may negatively affect drinking water quality by contributing elevated levels of DOC in comparison to other land uses. Because 50-100,000 acres in the Delta are slated for restoration, careful analysis of the effect of wetlands on dissolved organic carbon and DBP precursor loads is necessary. However, it should be noted that DOC is an inevitable component of natural waters and indeed, tidal wetlands within the Delta may not be the only important source for future emphasis. Balancing CALFED's goals to restore ecosystems in the Estuary with goals for improved source water quality will require blending science and management to find novel solutions.

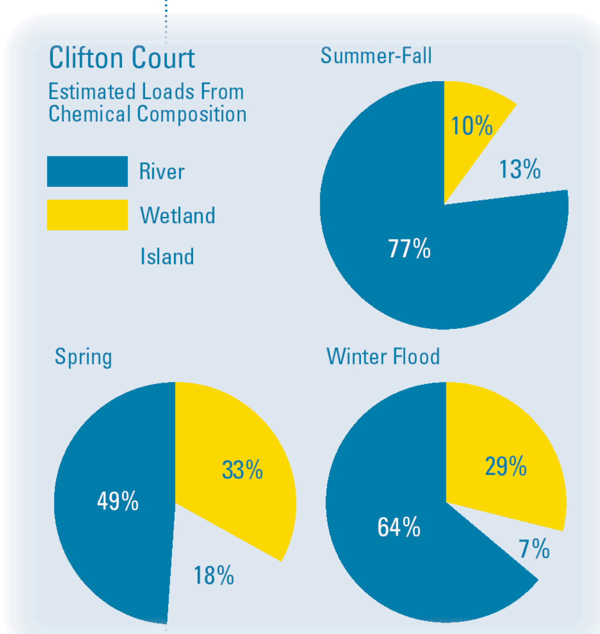


Figure courtesy B. Bergamaschi

SCIENTIFIC INFORMATION

- There is a popular misconception, even among some scientists, that dissolved organic carbon (DOC) is all the same, and that its concentration is what affects water quality. However, work extending back for several decades has shown that the type of DOC is as important as its quantity for the production of DBPs (Bergamaschi).
- Scientists have learned that there are other significant DOC sources within the Delta besides peat islands. In addition, less DOC is added to water overall from these sources in the Delta than was previously thought. There is a strong seasonal dependence on when DOC is added in the Delta (Bergamaschi).

The ELPH

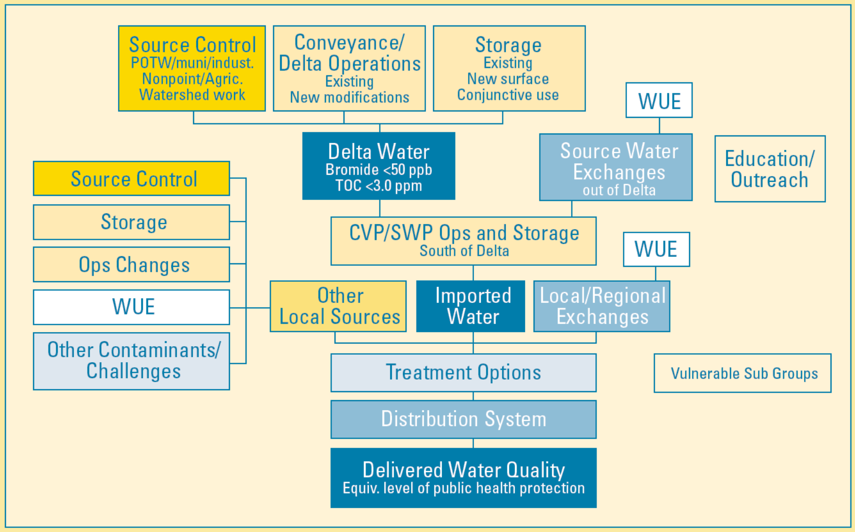


Figure courtesy CBDA

- Most of the DOC entering the State Water Project originates in rivers. Sources in the Delta contribute 25% of total DOC at State Water Project intakes. Most of this contribution occurs in the winter, and the main contributors are rivers, wetlands, and peat islands (Bergamaschi).
- We need more high-frequency monitoring at multiple locations to understand if CALFED management actions are having any positive ef-

MANAGEMENT IMPLICATIONS

- Distribution system improvements could contribute more actively to the ELPH framework. After treatment, recontamination can occur as water moves through transmission lines and distribution storage reservoirs (Macler).
- Ecosystem projects that impact water quality might benefit from advanced treatment to offset their effects, although this would require careful consideration (Glaze).
- Although utilities are generally in compliance with drinking water quality regulations, simultaneous compliance with multiple regulations may become more difficult. An example is the tension between corrosion control and adequate increased disinfection. Source water improvement may be necessary to meet future regulations (Macler).
- Currently, exports are operated to protect fish and water quantity. Water quality could be given higher priority in these management decisions (Macler, Bergamaschi).
- New disinfection byproduct concerns stem from tests of alternative disinfectants meant to avoid known disinfection by-products (DBPs). These alternatives generate new DBPs, including some potentially toxic ones such as iodoacetate and halonitro DBPs (Macler).
- In addition to source water protection, future tools to cope with these challenges may include decentralized treatment and dual pipe delivery of water of different qualities for drinking water and other uses (Salvia).
- Effective control of DOC also needs to happen upstream of the Delta (Bergamaschi).
- Results from experimental wetland demonstration ponds indicated that non-tidal wetlands contributed 10 times as much DOC and THMFP as nearby agricultural fields. Most of these loads were derived from seepage through shallow soils, and restoration designs should consider this pathway (Fleck).
- Surface water from restored wetland ponds contains DOC that is very reactive for DBP formation. However, this DOC is also probably important in the food web. CALFED will have to balance benefits of subsidence mitigation, habitat restoration and potential impacts on the drinking water supply (Fleck).
- Restricting drainage on Delta islands may provide a tool for reducing seepage and DOC loads to waterways (Deverel).

fect. DWR's Municipal Water Quality Investigation (MWQI) and others have conducted long-term monitoring of DOC in the Delta using, for example, monthly or biweekly grab samples. Analysis of this record has yielded valuable insights. However, river and tidal systems change rapidly, and the low frequency of past sampling limits our knowledge of historic DOC baseline levels, seasonality, and long-term trends. Continuous measurements, as are currently under way or planned, will provide a greater ability to understand the sources and impacts of DOC (Downing, Bergamaschi).

- One method to continuously monitor the quantity and source of DOC is to use the intrinsic chemical properties of UV absorbance and fluorescence. Development of spectral optical sensors that measure these properties in situ may provide reliable, high frequency data and can be used to calculate DOC and DBP precursor loads. These data may also be able to help identify DOC sources and detect separate organic and inorganic particulate fractions (Downing).
- Experimental sites on Twitchell Island were used to investigate the effects that wetland restoration will have on DOC and THM precursor loads from subsided peat islands. Subsurface flow through oxidized surface soils provide the greatest DOC loads to the channels. Wetland surface loads contribute smaller loads, similar in scale to present agricultural loads. However, DOC loads from wetland surface waters are higher in summer than in winter, opposite the trend of agricultural operations. Reducing subsurface flow will reduce total DOC load, but surface water processes produce DOC with higher propensity to form THMs suggesting both surface and subsurface flows will need to be minimized. (Fleck).
- For Twitchell Island agricultural drainage systems, the highest DOC loads and concentrations occur from December through April due to high groundwater levels and flow through highly organic soils. DOC quality also varies seasonally, with the highest specific trihalomethane formation potential and specific ultraviolet absorbance (SUVA, a measure of DOC quality) during low flow. Preliminary modeling indicates continuing subsidence will increase DOC loads in drainage resulting from increased seepage to islands. Subsidence mitigation wetlands would also increase DOC loads (Deverel).
- DOC samples from river water are younger than those from agricultural drain water, so authors attempted to use carbon-14 dating to identify the sources of DOC in Delta water. They found that modern-aged carbon is likely added to the older fraction somewhere in the Delta, and concluded that carbon-14 is not the best method to fingerprint carbon inputs to the system (DiGiorgio).
- Discharge from Natomas East Main Drainage Canal can contribute substantial TOC loads to Sacramento River during storm events, especially in initial fall storms. Cumulative discharges from urban sources in high-growth areas in the Delta and its tributaries could be significant TOC loading sources for drinking water intakes during these storm events (Zanoli).

Drinking Water Quality: Delta

Lisa Holm (CBDA)
Session Chair

Background

The Delta is a complex, highly managed water conveyance, ecosystem, recreation, and farming area. The Delta also supplies 23 million Californians with at least part of their drinking water, and there are a number of drinking water constituents of concern in Delta water. The presence of these constituents can be greatly influenced by water operational decisions, physical structures, ecosystem protection actions, and future actions contemplated by the CALFED Bay-Delta Program. The variability of the system is also of considerable concern, and in response efforts are underway to develop a real-time water quality monitoring, reporting, and forecasting system in the Delta.

The reason municipal water is filtered and disinfected prior to consumption is because of microbial contaminants in surface waters. While Delta drinking water intakes have recorded only low levels of infectious organisms – probably due to the low residence time of the Delta - *Cryptosporidium* and *Giardia* are present in Delta water. Both are protozoan parasites that can cause illness in humans, and can severely affect people with weak immune systems. U.S. EPA put forth new detection methods 1622 in 1999 and 1623 in 2001, but there was a need to test the effectiveness of these methods in the high turbidity conditions found in the Estuary. Boating, swimming and fishing activities introduce pathogens into the Delta, as well as unburned fuel from power watercraft leaks, and efforts are underway to quantify these impacts as well as to promote best management practices for their minimization.

The examples discussed in this session exemplify the broad range of water quality considerations in the Delta related to California's drinking water, the range of research CALFED is supporting to better understand these connections, and support the necessity for an equally broad view of protection of water quality (see p. 59 for more on ELPH).

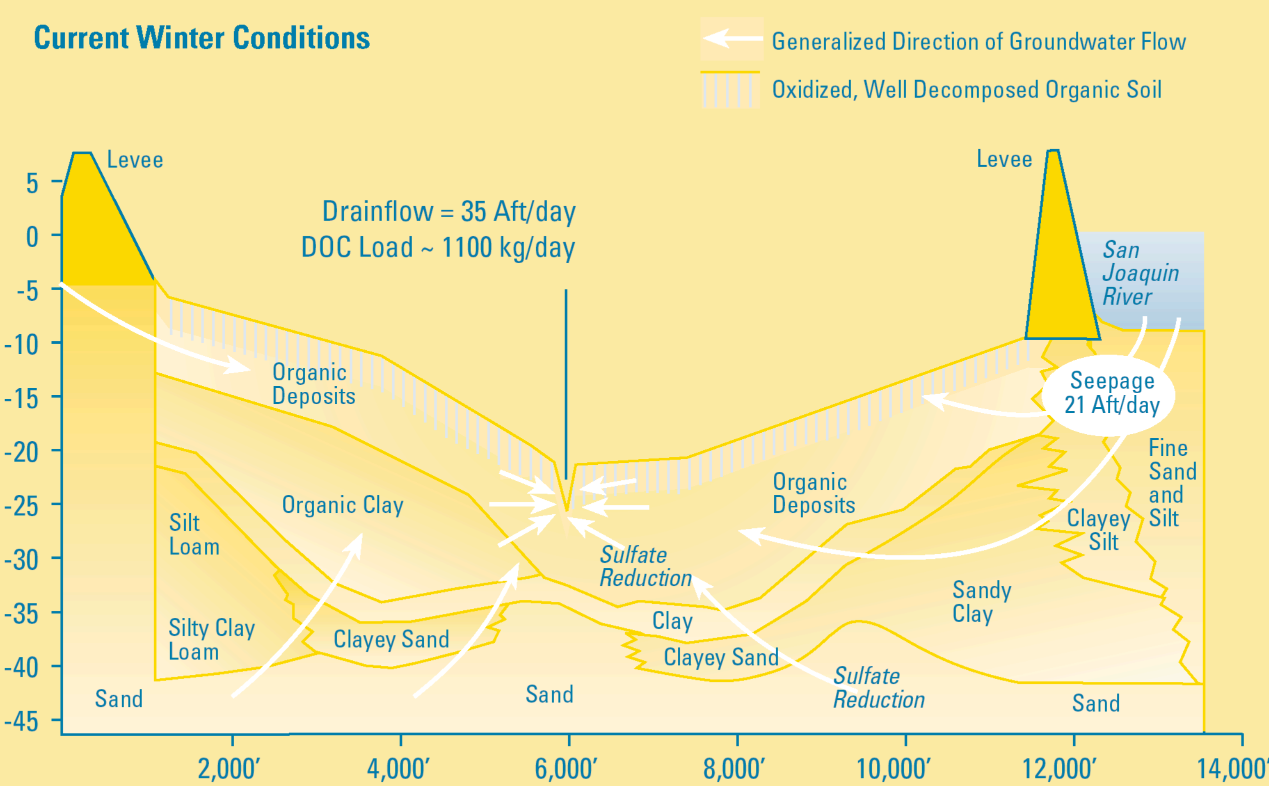
Banks Delta Pumping Plant

MANAGEMENT IMPLICATIONS

- EPA Method 1623 does not reliably measure the presence of *Cryptosporidium* and *Giardia*. The method may underestimate the prevalence of the organisms in drinking water (DiGiorgio).
- Resource managers need to consider the potential effects on water quality at drinking water intakes when planning Delta operations designed to protect aquatic species, and/or consider other actions to mitigate high salinity (Denton).
- During peak usage periods, Delta recreational activities can result in levels of fuel components and pathogens high enough to be a concern for drinking water quality. The amount of recreation-derived contaminants reaching south Delta drinking water intakes is highly sensitive to the timing and locations of recreational activities (Briggs).
- Water quality improvement actions will be more effective if they consider proximity of sources to drinking water intakes, magnitude of sources, and hydrodynamics (transport, travel time, and dispersion) (Briggs).
- Development of a network of real-time monitoring stations for TOC and anions at critical locations in the Delta and a system for disseminating the data rapidly will greatly enhance the ability of water managers to make informed decisions about Delta operations that may improve drinking water quality (Breuer).

SCIENTIFIC INFORMATION

- The ability of EPA method 1623 to detect *Giardia* and *Cryptosporidium* is affected by turbidity in source water, which is highly variable in the Delta. The characteristics causing turbidity also vary by location (DiGiorgio).
- Regulations designed to protect aquatic species in the Delta may affect water quality at drinking water intakes within the Delta. In particular, the shift of high exports from spring to fall to protect fish in the South Delta may increase salinity at the Contra Costa Water District intakes (CCWD). Analysis of historical water data suggests CCWD salinity increased because higher salinity water accumulated in the south Delta (Denton).
- In the south Delta during holiday weekends in 2003 and 2004, maximum concentrations of benzene, toluene, ethylbenzene, xylene, and MTBE at boating sites were similar to concentrations found in other high-use water bodies. Only benzene reached concentrations above drinking water standards. Concentrations of all compounds dropped rapidly, becoming nearly undetectable within three days after the peak. Pathogen concentrations were much lower than those during peak use periods at beaches and reservoirs, and were consistently higher in sites with restricted circulation (Briggs).
- Despite increasing boat use in the Delta, the estimated loads of fuel compounds to the south Delta have decreased from the 1990s to 2004 because of technological improvements in boat engines (Briggs).
- Automated sampling of Total Organic Carbon (TOC) and anions is being carried out at two Delta stations: the Sacramento River at Hood (TOC) and the Banks pumping plant (TOC and anions). Data are transferred to a central database, quality-assured, and then made publicly available (Breuer).
- Recent studies have detected low concentrations of anthropogenic endocrine disruptors, pharmaceutical compounds, and personal care products in the environments and in sources of public water supply. A model predicted that many pharmaceutical compounds will be present in secondary-treated sewage effluent, but that concentrations will be at or below current detection limits (Ongerth).



Delta Island agricultural drains are significant sources of DOC. This figure, a cross section of a Delta island, illustrates river water seeping through layers of carbon-rich soils before entering an agricultural drain to be pumped back to the river (figure courtesy S. Deverel).

Session Summary: Drinking Water Treatment Technologies

Pankaj Parekh (LADPW)
Session Chair

Background

CALFED's Equivalent Levels of Public Health Protection approach (ELPH, see p. 59) takes a holistic approach to improving drinking water quality. Drinking water suppliers prefer to have redundant protections in their systems, from source water to tap, as protective of public health. Ultimately, however, water treatment and distribution systems provide the last protective barrier for maintaining the quality of drinking water. In light of increasingly stringent regulations and degrading water quality, CALFED and individual utilities are investing significantly in plant renovations and in demonstrations of new treatment technologies. Results of two such studies and the results of modeling studies on future treatment needs were presented in this session, followed by a panel discussion. Both of the demonstration studies showed the effectiveness of new technologies, but one was uneconomical at a full-scale plant. The modeling study indicated that treatment plants will likely have to significantly upgrade under tightening regulations and degrading source water quality.

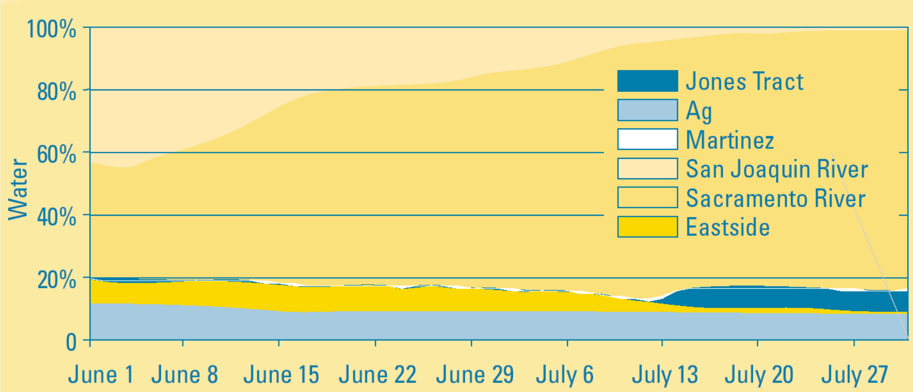
A panel discussion with all drinking water session chairs was held at the end of this session. Session chairs emphasized the need for better monitoring and assessment, the need to remain focused on multiple barriers of protection, and the complex and increasing pressures on providing healthful, aesthetically pleasing drinking water. For example, one panel discussant pointed out that the increase in the use of home treatment systems and of bottled water suggests consumers are not entirely satisfied with the product produced by water agencies. As source water quality deteriorates because of increasing population pressure, land use change, and other factors, treatment technology will remain an important component of the ELPH strategy.

MANAGEMENT IMPLICATIONS

- CO_2 treatment may allow some treatment plants to use water with higher bromide concentrations, providing more flexibility to Dealt water operations. However, if EPA's bromate standard tightens beyond 0.005 mg/L, the technology tested may not be economically feasible (Najm).
- While use of ion exchange resins can decrease TOC, bromide, and DBP precursors in treated water. Although the treatment is costly, its use might increase the range of options for water managers attempting to optimize the overall use of Delta water supply for all users, especially small treatment plants (Taplin).
- Future deterioration of water quality and/or tightening of DBP regulations will result in the need to upgrade drinking treatment plants using SWP water. Plants using current chlorine technology may become economically unfeasible with significant source deterioration. If the potentially enormous costs are to be avoided, the Delta must be managed to retain or improve its water quality (Najm).

SCIENTIFIC INFORMATION

- Full-scale experimental treatment with sulfuric acid or carbon dioxide (CO_2) suggests addition of CO_2 is a technically and economically feasible method for lowering pH of Delta water during treatment. This can limit bromate formation to meet current EPA regulations during ozonation of Delta water (Najm).
- Adding an ion exchange resin to normal treatment plant operation reduced total organic carbon (TOC) concentrations by 40-80% and bromide concentrations by 30-60%. It also reduced by half the trihalomethane (THM) and haloacetic acid (HAA) formation potential. In addition, it reduced the amount of alum required for water clarity, and decreased water quality variability. However, when tested in a full-scale traditional treatment plant, the resin was found to have an un-favorable cost-benefit ratio (Taplin).
- Deterioration of source water quality (or tightening of DBP regulations) will require changes at treatment plants. Simulations suggest plants will have to significantly upgrade their facilities, regardless of the treatment technology they use (Najm).



Volume fingerprinting in July 2004 suggested that a small but measurable fraction of water at the SWP Banks Pumping Plant originated at Jones Tract (figure courtesy R. Breuer).

Contaminants: Sources and Effects

Kathy Kuivila (USGS) and
Joy Cooke Andrews (CSU Hayward)
Session Chairs

Background

U.S. EPA defines contaminants as anything found in water which may be harmful to health. Contaminants have relevance for many of the CALFED program elements, including water quality, watershed management, ecosystem restoration and environmental justice. All of these issues are, or should be, informed by the best available science.

Contaminants found in the Estuary are too numerous to list here, but scientists presented work relevant to many of them. PCBs and dioxins are of greatest human and wildlife health concern. Selenium is a reproductive toxin to wildlife and humans at high enough concentrations. Mercury is a potent neurotoxin impacting wildlife and humans in its methylated form (methylmercury). (More mercury basics can be found in the mercury session on p. 59) Approximately 400 million cubic meters of mercury-laden mining debris were deposited in North San Francisco Bay during the 1800s (Higgins). Many legacy contaminants partition more to sediment than to water, and these sediments can remain biologically active for decades. Most of these contaminants can bioaccumulate up the food chain.

Sediment and contaminants are inextricably linked in San Francisco Bay. Attempts to manage them complement each other, but may overlap:

- In the Bay, a Long Term Management Strategy (LTMS) guides dredged sediment disposal. Its guidelines include maximizing the beneficial use of dredged material as a resource when environmentally responsible.
- Two sections of the Clean Water Act are relevant for sediment disposal. Section 404(b)(1) stipulates that fill material not be discharged if it may elicit an unacceptable adverse ecological impact, and Section 303(d) regulates "impaired water bodies" on a contaminant-specific basis. All areas of the Bay are on the 303(d) list for PCB's, OC pesticides, and mercury.
- The SF Bay Water Quality Control Plan (Basin Plan) contains numerical Water Quality Objectives for discharges to the Bay and its tributaries. These require that runoff from sediments be contained. In effect, this regulation means that disposed sediments must be stored in ponds while water evaporates.

In San Francisco Bay industrial and municipal wastewaters are generally insignificant contaminant sources compared to agricultural and urban runoff. Regulation of point sources has worked – non-point sources will be the next great management challenge. Major uncertainties in load estimates and the role of hydrology and sediment discharge may complicate such efforts.

MANAGEMENT IMPLICATIONS

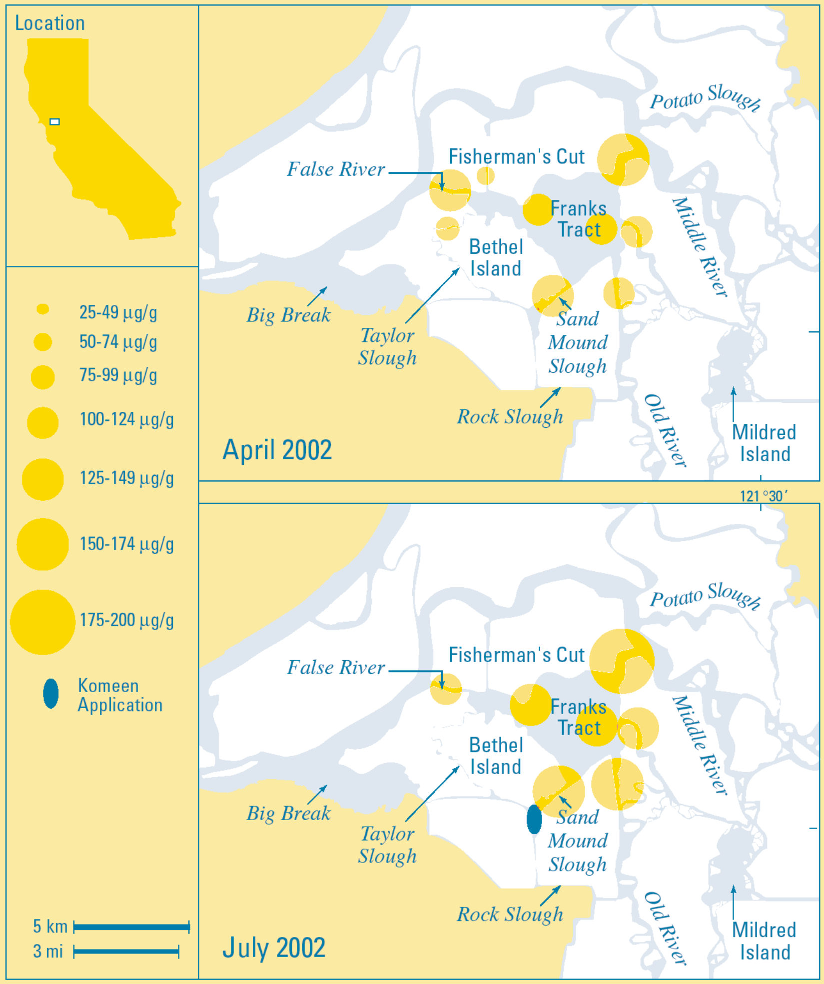
- Attainment of water quality objectives will take decades because large sources of legacy contaminants are stored in Central Valley sediments and can be re-suspended (Connor).
- Flooding of the Yolo Bypass could contribute to suspended sediment loads and mercury into SF Bay, and may result in increases in contaminants (McKee).
- Reducing the volume of dredged material disposed in San Francisco Bay through upland sediment placement will result in a net reduction in mercury inputs, but will likely lead to increased methylmercury production. Application of aeration systems to dredged sediments during dewatering could limit methylmercury formation in upland disposal sites (Bodensteiner).
- Copper in Komeen trials appeared to be bioavailable to *Corbicula*. This supports the hypothesis that copper entering the aquatic ecosystem through herbicide applications enters the food web and increases the copper body burden in Delta clams. Wildlife that consume *Corbicula* in the Delta may be exposed to high concentrations of copper after a Komeen application (Brown).
- Urban runoff is a significant source of PCBs and Organic Contaminant pesticides in the Guadalupe River watershed (Leatherbarrow).

SCIENTIFIC INFORMATION

- The fate of estuarine contaminants depends largely on sediment dynamics (resuspension and remobilization of stored contaminants into the food chain). Buried contaminants can be exposed by erosion and released to the environment (Higgins, McKee).
- A GIS model of the spatial distribution and depositional history of recent sediments in the Estuary suggests about half of the sediment deposition from the 1800s remains in San Pablo Bay. Recent sediment overlies contaminated sediment in parts of San Pablo Bay (Higgins).
- Mercury in suspended sediments is a significant source of current mercury loading into SF Bay. As suspended sediment inputs decrease, erosion may increase in the Bay-Delta system, causing remobilization of buried mercury (McKee).
- PCBs and some OC pesticides correlate with suspended sediment discharge from the Guadalupe River in 2003. Concentrations spanned an order of magnitude. The rising stage

-continued

Mean Copper Concentrations in *Corbicula*



Clams in sloughs and rivers to the east of Franks Tract had significant copper concentrations in their tissues eight months after the application of Komeen (an herbicide containing copper) (figures courtesy C. Brown).

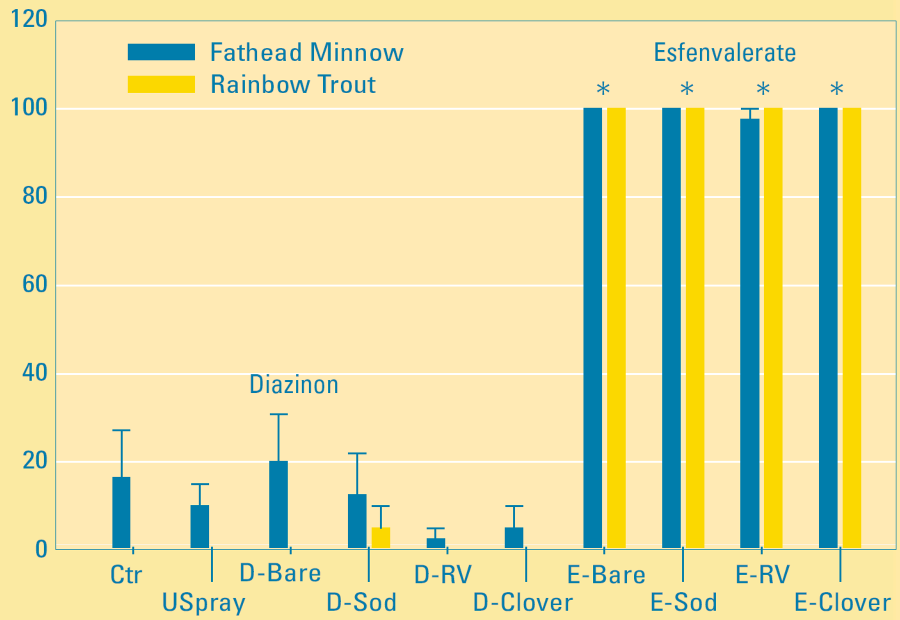
- Effects of selenium on white sturgeon embryos increased significantly when 15 ppm or greater was microinjected. Since eggs collected from the Estuary can be in excess of 29 ppm selenium, embryo toxicity is likely in wild populations (Linville). (see Ostrach, page 20).
- Pesticides may act synergistically with pathogens to compromise the health of fish populations. Effects include decreased swimming performance, feeding success and growth, and cellular and tissue damage. Scientists are just scratching the surface in finding the sublethal effects in fish from pesticide exposure (Werner). (See Ostrach, page 20).
- New modeling allows calculation of dose-response effects for populations and individuals moving through contaminated areas. This model can more accurately represent effects of contaminants in dynamic ecotoxicology situations than laboratory-based dose-response curves (Ginn)
- Three facts about pyrethroid pesticides run counter to common understanding. 1) Pyrethroid pesticide use is decreasing in absolute terms, but current use pyrethroids are much more toxic than older ones. 2) Most analytical labs are able to detect acutely toxic concentrations of pyrethroids in water or sediment samples. 3) Sediment bound pyrethroids are bioavailable, but effects on sediment-dwelling organisms and biomagnification are unknown (Weston).

SCIENTIFIC INFORMATION CONTINUED

of the hydrograph had the highest suspended sediment and PCB, cadmium, copper, and zinc concentrations and was likely composed of highly urban lower watershed sources. The falling hydrograph had high levels of mercury, nickel, and chromium, and was likely composed of upland, non-urbanized runoff. These data suggest the urban areas of this watershed are a significant source of PCBs and OC pesticides (Leatherbarrow).

- In laboratory simulations of dewatering of upland sediment ponds, direct aeration substantially reduced the capacity of sediments to generate methylmercury, relative to stagnant evaporation and flow-through de-watering (Bodensteiner).
- Komeen, an herbicide containing copper, is being tested for eradication of the invasive aquatic weed *Egeria densa*. After Komeen application in Franks Tract, copper in water rapidly decreased within 48 hours, but copper concentrations in nearby clams doubled. Clams in sloughs and rivers to the east had significant copper concentrations in their tissues eight months after the application, as did clams from locations west and north, but to a lesser extent. Biodynamic modeling suggests the copper persisted in clam tissues either because of slow loss rates or environmental recycling (Brown).
- White sturgeon (*Acipenser transmontanus*) in the Bay-Delta are prone to selenium bioaccumulation because of their long life-span and benthic feeding habits. Selenium levels in maternal tissue and ovulated eggs correlated with development abnormalities and decreased embryo survival. White sturgeon transfer selenium to their offspring (Linville). (See Ostrach page 20 and Fish Protection page 10).
- Scientists typically characterize toxic effects with dose-response models based on laboratory data. A new modeling technique combines population dynamics, river flow movements, and species movements into a new measure for dose-response effects for populations in motion through contaminated environments. The model successfully modeled the current state of juvenile Chinook salmon susceptible to disease in waterways of the Pacific Northwest (Ginn).
- Exposure of juvenile salmon to the pesticides chlorpyrifos or esfenvalerate resulted in a significant increase in heat shock/stress proteins, cytokine induction and inhibition of acetylcholinesterase enzyme activity. Sublethal effects were additive, and also increased susceptibility to infectious hematopoietic necrosis virus (IHNV). Fish mortality increased with exposure to virus and pesticide (Werner).
- Overall use of pyrethroids is lower than during the 1990s, but newer synthetic pyrethroids are much more toxic than Permethrin, the most common pyrethroid used in the 1990s. The total amount of toxicity from pyrethroids has actually increased. Sediment bound Permethrin was bioavailable to worms in laboratory tests (Weston).

Mortality of Fathead Minnow and Rainbow Trout Larvae Exposed to Stormwater Runoff from a French Prune Orchard



Percent mortality of fish Larvae exposed to runoff from the first storm after application of pesticide in a prune orchard. Runoff from esfenvalerate-treated sections resulted in greater mortality than control or diazinon-treated sections. (Ctr -control; Non-sp - nonsprayed; Bare - no ground cover vegetation; Sod - perennial sod; RV - resident vegetation; Clover – nontillage clover.) (figure courtesy I. Werner).

Water and Sediment Quality

Christopher G. Foe (CVRWQCB)
Session Chair

Background

Alterations to an already heavily-engineered Delta can profoundly affect water quality management of in-Delta waterways. Talks on improving and managing sediment and water quality in the Bay-Delta and its tributaries focused on three sub-topics: Delta waterways, the Stockton Deep Water Shipping Channel (DWSC), and impacts of dams. It is not news that engineered solutions that provide for beneficial uses of water can have unanticipated detrimental impacts. Scientists have applied new tools to understand some examples more clearly: Local diversions, barriers and the SWP pumps, all of which are in place to improve water supply for beneficial uses, can each impact not only flows, but also water quality. Proposed projects on Webb Tract and Bacon Island represent potential in-Delta storage opportunities and potential new habitat. However, the large, still bodies of water that would be created would likely produce excess dissolved organic carbon (DOC), which may ultimately impact drinking water quality (see Drinking Water Quality, page 59). One large-scale alteration to the Delta is the dredged Stockton Deepwater Shipping Channel (DWSC). A persistent water quality problem in the DWSC is its low summer dissolved oxygen (DO), which may be a barrier to upstream migration of returning adult salmon.

Most California rivers are dammed. Impounded rivers often do not receive annual floods that maintain geomorphic and ecosystem integrity. Controlled reservoir releases have been proposed to help replicate the natural benefits of annual floods, but it has been unclear what impacts these releases may have on water quality downstream. Dam removals are widely recognized as a future inevitability because of finite structural lifetimes, but also in some cases for habitat restoration. However, few case studies have investigated the impacts of dam removal on downstream water quality.

Methodology is also relevant here. Hydrodynamic modeling studies have had increasing policy influence in recent years with their increasing sophistication, power, and visual appeal. Such studies will always go hand-in-hand with empirical work in a complex system such as the Estuary, particularly where biology is involved. Together, these approaches can build an overarching, systemic approach to understanding our impacts on the Estuary's water quality, and how we can most effectively manage it (see p. 59).

SCIENTIFIC INFORMATION

- Analysis of water quality time series suggests water diversions and in-Delta barriers can have profound, large-scale effects on the Delta water quality parameters, and thus on ecosystems:
  - The SWP's H. O. Banks pumping plant water exports tend to draw fresh Sacramento River waters to the South Delta, but reduce overall South Delta salinity at Mildred Island.
  - A barrier installed at the head of Old River can increase DO levels in the Stockton Deepwater Shipping Channel by routing more of the San Joaquin River flow through the shipping channel and thereby reducing in-channel residence time. However, temporary barriers installed in the South Delta isolate a large portion of the South Delta from exchange with neighboring waters. Their subsequent removal can increase DOC levels in waters exported at the Banks pumping plant (Monsen).
- There has been relatively little change in Suisun Bay salinity since 1921, even though Delta exports have reduced freshwater outflows by up to 22%. Most of the temporal variability in Suisun Bay salinity can be attributed to decadal scale changes in climate, and not necessarily to in-Delta diversions (Enright).
- A numerical model of the San Francisco Estuary was used to evaluate the impacts that bathymetric changes may have had on long-term salinity trends. Modeling circulation with Suisun Bay at its shallower 1922 depth suggests deepening of Suisun Bay since 1922 has tended to make Suisun Bay saltier than it would be with shallower bathymetry (Enright).
- Anthropogenic features such as shipping canals, tow drains, straight line cuts, and the Delta Cross Channel have also impacted salinity in the Delta. Modeling with these features removed suggests in-Delta water exports effectively change the seasonality of outflow to Suisun Bay. Addition of the Delta Cross Channel waterway has made the North Delta fresher and the Central Delta saltier. Modeling with all of the shipping channels removed makes the South Delta noticeably saltier (Enright).
- Modeling experiments show that if water stored on proposed Bacon

-continued

MANAGEMENT IMPLICATIONS

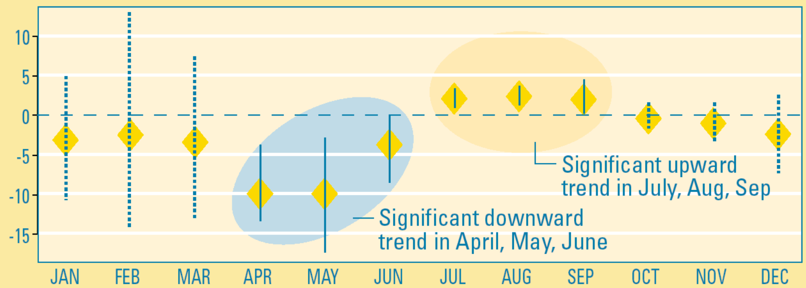
- Delta barriers and diversions could be used to improve water quality. If a relationship between the Old River barrier and Stockton shipping channel DO holds true, then the barrier could be used to increase flow and decrease water residence time in the DWSC during low DO episodes. Exports at Banks could be effectively "timed" relative to South Delta Barrier installation/removal events to control DOC levels in the exported waters. (Monsen) (see also Drinking Water Quality, page 59).
- In order to manage the Estuary as a system, managers need to understand that diversions can reduce the capacity of aquatic ecosystems to assimilate wastes, and that local small-scale diversions can have regional large-scale effects (Monsen).
- Interbasin transfers to meet water-supply demands can conflict with goals of providing safe drinking water and rehabilitating populations of at-risk species and their supporting functions. The need to balance numerous competing beneficial uses of Delta water could benefit from a broader framework of water-resource management that explicitly recognizes the interconnections between hydrologic manipulations, water quality, and the status of aquatic ecosystems (Monsen).
- Modeling suggests discharge from in-Delta storage on Bacon Island and Webb Tract may only have minor deleterious impacts on DO or temperature of adjacent waterways. However, it is not clear whether the assumptions in this modeling could be met (Rajbhandari).
- High flow rates (> 1500 cfs) in the San Joaquin could increase DO in the DWSC. Pumping at Banks and Tracy can drastically slow flushing of the shipping channel. One way to provide adequate flow without reducing export might be to divert most of the San Joaquin's flow through the DWSC. Reducing nutrient inputs from agricultural discharges and drainage into Mud and Salt sloughs could also improve DO levels (Lee, Van Nieuwenhuyse).
- The entire diel cycle may need to be sampled to compute daily algal loads in the San Joaquin River (Dahlgren).
- If phosphorous loads in the San Joaquin could be reduced from the present 960 metric tons/yr to about 550 mt/yr by 2035, marked improvement in Stockton shipping channel DO may result. This would require reducing P concentrations to 130 mg/m3. Eliminating the P load from just Salt Slough might achieve this goal (Van Nieuwenhuyse).
- Small bottle incubations could be used to test the "health" of Bay-Delta waters. If nitrate drawdown does not occur within three-four days, then something else is limiting productivity (Dugdale).
- After dam removal, gravel/cobble controls in the river bed may control sediment mobilization and minimize N remobilization from reservoir sediments. The gravel control strategy is not recommended, however, if the goal is to restore spawning beds for fish (Ahearn). (see also Miller, page 34)
- Controlled water releases were often accompanied by short-lived increases in fecal coliform, turbidity, and total suspended sediment. Coordination with water export activities could avoid impacts to drinking water quality (Henson).

SCIENTIFIC INFORMATION CONTINUED

Island and Webb Tract projects can be held at or above 6.0 mg/l DO, then discharge of these waters into adjacent waterways may have no deleterious impacts on their DO. The vast majority of discharge events would reduce adjacent waterways' DO by less than 1.0 mg/l. However, it is unclear how on-island reservoirs' DO could be maintained above this level for any significant period of time (Rajbhandari).

- In temperature modeling scenarios, the adjacent waterway was usually warmed by less than 2.0 ºC, resulting in only rare deleterious increases. (Deleterious temperature increases were defined based on existing temperatures, with greater increases allowed at lower temperatures) (Rajbhandari).
- Two main causes of the DWSC's low DO are a) City of Stockton wastewater ammonia and b) algal biomass that develops upstream in the San Joaquin River. Both exert oxygen demand within the channel. However, long water residence times in the shipping channel also contributes to low DO – the relatively slow flushing allows time for more decay of organic matter and a higher oxygen demand to be exerted. A flow of 1500 cfs or greater may provide enough flushing to avoid low DO conditions (Lee).
- Over a five-year algal abundance record, chlorophyll levels correlated well with temperature in the DWSC. In wintertime, chlorophyll levels are usually over 5 mg/l , while in summer they often exceed 70 mg/l (Dahlgren).
- On the San Joaquin River, chlorophyll levels were lowest in the mid-morning at upstream sites and lowest at noon at Vernalis.

Slope of Delta Outflow Trend (1929-2002)

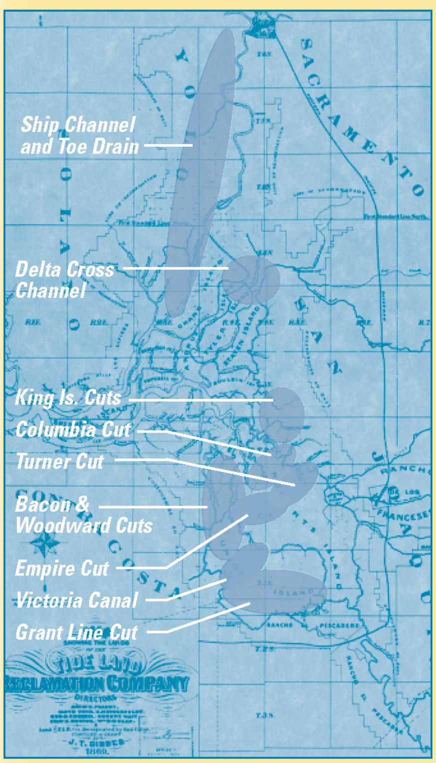


Water projects have re-distributed outflow seasonally. Data from 1929-2002 show a significant downward trend in April-June, and a significant upward trend in July-September (figure courtesy C. Enright).

Levels peaked in the evening. Daily changes in dissolved oxygen and pH suggest chlorophyll levels were driven by algal growth. The evening/nighttime reduction in chlorophyll was likely due to zooplankton herbivory. Invertebrate populations increased dramatically in the evening, possibly hiding to avoid predation during daytime and emerging at night to graze the daily phytoplankton bloom (Dahlgren).

- Globally, lakes and rivers' chlorophyll levels correlate with phosphorous levels, suggesting a possible management tool to reduce oxygen demand. Phosphorus concentrations in the San Joaquin River are high making it questionable whether sufficient reduction could be achieved to limit algal growth. However, in a somewhat analogous situation, from 1977–2003 phosphorous levels in the Rhine River were reduced from 700 to 200 mg/m^3, accompanied by a dramatic decline in chlorophyll levels. All these phosphorus levels are above concentrations limiting algal growth in laboratory studies. Dissolved oxygen levels in the Rhine recovered dramatically during phosphate reduction (Van Nieuwenhuyse).
- Enclosures of San Francisco estuary water were used to evaluate the efficacy of ammonium in suppressing phytoplankton blooms. Nutrient levels were rapidly depleted after 2-4 days. However, nitrate consumption did not start until ammonium levels had been reduced to near zero. Diatoms typically formed a substantial bloom within 3 days, eventually reducing nitrate levels to near zero. In experiments where nutrients or light were reduced, the phytoplankton response was delayed (Dugdale).
- The primary impact of dam removal on Murphy Creek was mobilization and oxidation of ammonia in sediments. The nitrification process within the restored reach produced substantial NO_3. During fall and early winter, in-sediment nitrification caused high sediment NH_4 levels to be accompanied by high dissolved NO_3. During wintertime, the nitrification slowed and NO_3 levels were fairly low. In spring and summer, aquatic photosynthesis consumes most of the NO_3 produced by in-sediment nitrification (Ahearn A).
- Downstream water quality changed in response to a controlled release from Camanche Dam on the Mokelumne River. Fine-grained sediments were effectively flushed out of the system above a critical water transport threshold. With each successive pulse increase in transport, coarse sediments were suspended and then re-deposited (Henson).
- Successive increases in water transport during the Comanche Dam release were accompanied by short-lived "spikes" in total suspended sediments (TSS), total nitrogen (TN), total phosphorus (TP), and fecal coliform. The unimpounded reaches of the river were a net source of TSS, TN, and TP, yet acted as a sink for dissolved nutrients nitrate, ammonium, and phosphate. Lake Lodi acted as a sink for TSS, TN and TP, and a source for nitrate, ammonium, and phosphate. (Henson).

North & South Delta 1869



A comparison of historical maps to current ones shows that human actions have dramatically changed the physical configuration of the Delta in the past 150 years (maps courtesy DWR).